A case for optimising fracture healing through inverse dynamization

Epari DR¹, Wehner T², Ignatius A², Schuetz MA¹, Claes LE²

¹Institute of Health & Biomedical Innovation, Queensland University of Technology, Brisbane, Queensland, Australia
²Institute for Orthopaedic Research and Biomechanics, University of Ulm, Ulm, Germany

Corresponding author:
Devakara R. Epari
Institute of Health and Biomedical Innovation
Queensland University of Technology
60 Musk Avenue, Kelvin Grove, Queensland 4059, Australia

E-Mail: d.epari@qut.edu.au

Conflict of interest/role of funding source:
The authors have no conflict of interest to declare. This work received no funding.

Keywords: bone healing, dynamization, fixation stiffness, interfragmentary movement
ABSTRACT

The mechanical conditions in the repair tissues are known to influence the outcome of fracture healing. These mechanical conditions are determined by the stiffness of fixation and limb loading. Experimental studies have shown that there is a range of beneficial fixation stiffness for timely healing and that fixation stiffness that is either too flexible or too stiff impairs callus healing. However, much less is known about how mechanical conditions influence the biological processes that make up the sequence of bone repair and if indeed mechanical stimulation is required at all stages of repair. Secondary bone healing occurs through a sequence of events broadly characterised by inflammation, proliferation, consolidation and remodelling. It is our hypothesis that a change in fixation stiffness from very flexible to stiff can shorten the time to healing relative to constant fixation stiffness. Flexible fixation has the benefit of promoting greater callus formation and needs to be applied during the proliferative stage of repair. The greater callus size helps to stabilize the fragments earlier allowing mineralization to occur faster. Together with stable/rigid fixation applied during the latter stage of repair to ensure mineralization of the callus. The predicted benefits of inverse dynamization are shortened healing in comparison to very flexible fixation and healing time comparable or faster than optimum (stable) fixation with greater callus stiffness.
INTRODUCTION

The majority of fractures heal with the formation of an external callus. This process, known as secondary bone healing, occurs when there is relative movement between the fracture fragments or interfragmentary movement (IFM) [1]. This process of repair can be divided into several overlapping stages. Healing begins with inflammation and formation of a haematoma. Proliferation follows during which the haematoma is converted to fibrous tissue and cartilage and the formation of hard callus by intramembranous ossification takes place. During the consolidation phase, the soft cartilaginous callus undergoes mineralisation via endochondral ossification. Once the fracture is bony bridged, the callus is remodelled and finally resorbed returning the bone to its original state [2].

Adequate blood supply and stable fixation are a necessity for timely healing. Generally, the size of the external callus produced is related to the flexibility of fixation [3]. Overly rigid fixation suppresses callus formation [4], whereas instability leads to formation of large callus that fails to bridge, also known as a hypertrophic non-union [5]. Investigations of the influence of controlled micro-motions on the healing of bone fractures have determined that moderate axial IFMs reliably produce a timely healing outcome [4,6-8].

The magnitude of IFM is determined by the stiffness of fixation, the degree of limb loading and the stiffness of the healing tissues. In the normal course of healing IFMs are largest during the initial stage of healing, when the callus is filled with haematoma and soft fibrous tissue [8,9]. As the callus increases in size and the tissues mature callus stiffness increases and IFMs reduce in magnitude until finally bony bridging can occur (Figure 1). Following bony bridging callus stiffness continues to increase as remaining areas of the callus are mineralized [10] and
remodelled replacing woven bone with lamellar bone [11,12]. A maximum in callus stiffness is reached as the balance between callus remodelling and resorption shifts in the favour of the latter [13].

Whilst the influence of mechanics on the healing outcome is well established, it is not clear which processes and stages of repair are mechano-sensitive. Therefore, it is not known if mechanical stimulation is needed during all stages of repair nor how the optimal IFM may differ at various stages of repair.

Histology from an ovine model of bone healing can provide insights into the influence of mechanics on the formation of the mineralized callus during the early proliferative stage of healing. The tibial osteotomy stabilized with an unilateral external fixator produced distinct differences in the mineralized callus formation on the medial and lateral aspects of the bone after two weeks of healing (Figure 2). Under unilateral external fixation, the predominant mode of deformation is axial compressing with superimposed bending due to the eccentric location of the fixation, resulting in greater amounts of compressive interfragmentary movement occurring on the far cortex compared to the fixation near cortex. This example illustrates two important elements. The amount of hard callus formed is related to the local mechanical conditions and within the same time frame a larger external callus can be formed when larger movements are present.

Comparing healing under varying degree of stability, it is known that overly flexible fixation delays healing in terms of time to bridging and leads to formation of a larger callus. Furthermore, comparing the histological evolution of osteotomies stabilized under varying degree of fixation, it was concluded the later chondral phase of healing was prolonged under more flexible conditions [14]. It might be inferred by this observation that mineralization of the callus and bridging is impaired by
excessive tissue loading or interfragmentary movement and that bridging requires stability. Hence, it may be beneficial to stiffen fixation during the callus consolidation phase to reduce the IFM and resulting tissue strains enabling endochondral and intramembranous ossification and permit bony bridging to occur and to eliminate potentially disruptive loading events.

Therefore, flexible fixation, which is capable to stimulate a larger callus, may also during the later stages of healing make callus bridging vulnerable to high loads. Given that an individual stumbling without falling can easily produce loads of up to 9 times body weight in the lower limb [15]. These forces arising largely from muscle contraction could easily produce IFMs capable to disrupt the healing tissues and delay healing.

**HYPOTHESIS**

The ability to modify the stiffness of fixation has the potential to enable mechanical stimulation during periods of healing when they are needed and to shield the tissues from potentially disruptive loading and IFMs when stimulation is not required. Based on the influences theorized above, we hypothesize that the optimum fixation of a fracture is flexible fixation during the early phases of healing and rigid fixation during the later stages of repair. A procedure referred to here as inverse dynamization.

**CONSEQUENCES OF THE HYPOTHESIS AND DISCUSSION**

The predicted benefits of inverse dynamization on bone healing in terms of IFM and callus stiffness compared to stable and flexible fixation is depicted in Figure 3. Stable fixation is defined here as the “theoretical optimum” fixation stiffness (unchanged over course of healing) that results in the shortest time to healing in terms of reduction of IFM and time to bony bridging. Flexible fixation is less stiff than the
stable fixation defined above, but is within the range that healing still occurs. Inverse dynamization constitutes a change from flexible fixation to stable fixation.

Considering first the time to bridging as indicated by the IFM. Flexible fixation produces larger IFMs that take longer to reduce compared to the stable fixation stiffness. We predict that inverse dynamization will lead to a shorter or comparable time to bony bridging compared to the “theoretical optimum” stable fixation. This acceleration of healing is achieved through a combination of factors that result in low IFMs and strains in the soft-tissues permitting faster mineralization via both intramembranous and endochondral ossification. Firstly, a larger mineralized callus, resulting from flexible fixation during the early proliferative stage, acts to increase the load-sharing area and thereby reducing the tissue strains. Secondly, the stiffening of fixation in the later healing phase will reduce IFM and thus strains in the healing tissues. The combination of these two factors reduces strains in the soft-tissues to below levels from stable fixation alone permitting an accelerated mineralization of the soft callus and bridging.

In addition to a shortened healing time, is predicted that inverse dynamization will result in greater callus stiffness comparable to stable fixation. The larger callus developed due to early flexible fixation will result in a larger final callus and hence greater callus stiffness.

In summary, the predicted benefits of inverse dynamization are

- Shortened healing in comparison to very flexible fixation and healing time comparable or faster than optimum (stable) fixation
- Greater callus stiffness providing increased safety factor with respect to re-fracture following implant removal.
REFERENCES


Figure 1 Over the normal course of bone healing, interfragmentary movement (red) decreases whilst callus stiffness (green) increases. The cessation of interfragmentary movement coincides approximately with bony bridging of the callus. Following bony bridging callus stiffness continues to increase as the remainder of the callus is mineralised and remodelled. Callus stiffness reaches a maximum as resorptive activity becomes dominant returning the bone to close to its original anatomy. Time to healing indicated by interfragmentary movement (dashed vertical red line) occurs earlier than maximum callus stiffness (dashed vertical green line).
Figure 2 Histological section taken after two weeks of healing in an ovine osteotomy model of bone healing. The fragments were stabilized with external fixation on the medial side of the tibia (right side in above). After two weeks greater callus size and mineralisation can be clearly seen on the lateral side (far cortex), where the greatest interfragmentary movement can be expected to occur under uni-lateral external fixation [14].
Figure 3 Illustrates the hypothesized benefit of inverse dynamization on interfragmentary movement (left) and callus stiffness (right) over the course of healing. Inverse dynamization shortens the time taken for IFMs to fall compared to flexible fixation and stable fixation. Additionally, inverse dynamization results in a callus with a higher stiffness than that resulting from stable fixation and almost as high as that resulting from flexible fixation. Curves are illustrative only.